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Infall and accretion

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Abstract. Gas infall and accretion play a fundamental role in galaxy formation, and several processes of accretion are reviewed. In particular the cold accretion may solve to some extent the angular momentum problem in disk formation, while it is aggravated by mergers. Gas accretion is one of the main actor in secular evolution: it is required to account for recurrent bar formation, and to explain the feedback cycles of formation of bulges and black holes, with correlated masses. Infall is also required to fuel a regular and almost stationary star formation history. Star formation is quenched for galaxy in clusters when gas accretion is suppressed through stripping. The central brighter central galaxy can benefit however of gas accretion through cooling flows, moderated by AGN feedback. Hot and cold feedback scenarios can be considered, to account for a stationary cooling flow, and explain the filamentary CO and H α observed structures.

1. Cold gas accretion on galaxies

According to the conventional scenario of the Λ CDM hierarchical galaxy formation, mass is assembled by mergers essentially, and the baryonic gas is shock heated to the virial temperature of the total structure (10^6 K for a Milky Way-type galaxy), before being accreted, as far as the hot gas cools down. This scenario ignores the possibility of dense gas present in contrasted structures, that can cool much quicker, and radiate its gravitational energy while remaining cold. Numerical simulations with enough resolution show now clearly two modes of accretion (Keres et al. 2005): hot gas accretion, mainly around massive structures, where shocks can be violent, and cold gas infalling along filaments, the fraction of cold gas being larger in low-mass haloes ($M_{CDM} < 310^{11} M_{\odot}$). The cold gas accretion dominates at high redshift. In addition, the star formation rate history follows intimately the total gas accretion, as shown in Figure 1.

The observation of a clear bimodality between galaxies – a blue sequence still accreting gas and forming stars, while the red sequence consists of massive red galaxies, in general in rich environment, where gas and new stars are absent – has been interpreted by the existence of these two modes of gas accretion, by Dekel & Birnboim (2006). Below a certain halo mass of $\sim 10^{12} M_{\odot}$, the accretion shock is not sufficient to heat the gas to the virial temperature, and galaxy disks can be formed by cold gas flows, yielding efficient star formation. While in more massive structures, the gas heated by shocks is diluted, and sensitive to feedback due to active nuclei, quenching star formation, and producing "red and dead" galaxies, which today do not evolve any more, their observed properties changing only as expected for passive evolution.

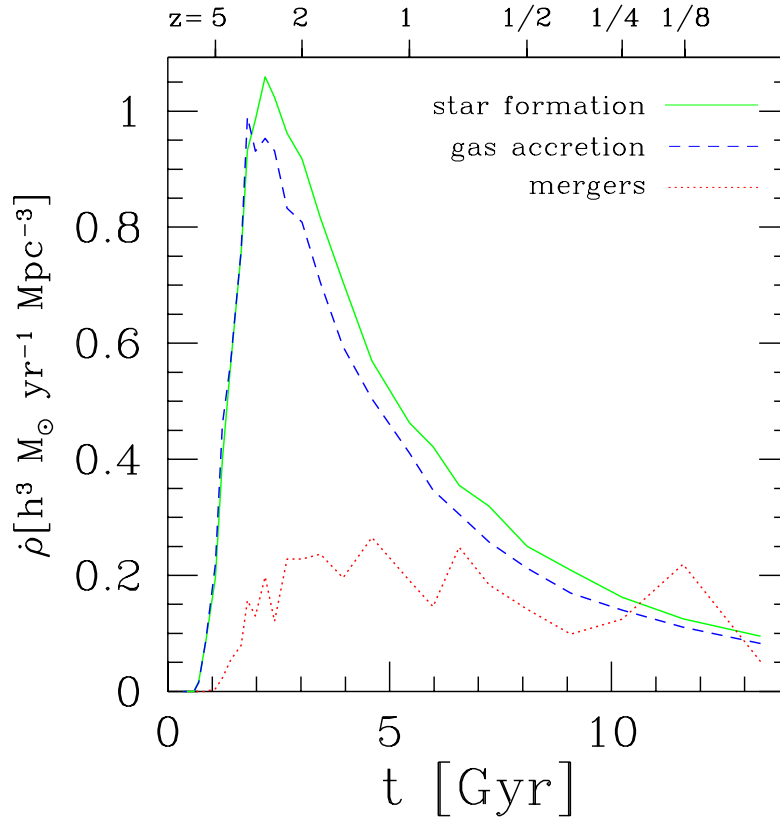


Figure 1. Comparison as a function of time of the star formation rate (solid line, green), the smooth gas accretion rate onto simulated galaxies (dashed line, blue), and mass gained in mergers (dotted line, red), by Keres et al. (2005).

The bimodality is observed on big samples of galaxies (SDSS, 2dF, MGC.), and separates clearly the early-type "red" galaxies from the late-type "blue" ones, according to their stellar distribution (Sersic index, for example), or their surface density at effective radius. The total galaxy mass is related to this separation, the red sequence being more massive (e.g. Driver et al. 2006). This observation is also reflecting the downsizing phenomenon: early-type galaxies appear to have formed the majority of their stars very early in the universe, while star formation is going on now in smaller spirals and dwarfs. Is this incompatible with the hierarchical scenario?

2. Star formation history and surface density

In fact, the two sequences of galaxies are distinguished by their stellar surface densities (Kauffmann et al. 2003). Low Surface Density (LSB) galaxies are small spirals or dwarfs, with high gas content, high and young star formation, while

High Surface Density (HSB) are massive early-type galaxies, with concentrated mass, characterised by an old stellar population. The transition occurs at the visible mass of $310^{10} M_{\odot}$, or stellar surface density of $3 \cdot 10^8 M_{\odot}/\text{kpc}^2$. But star formation histories are more strongly correlated with surface mass density than with stellar mass.

This observation could be interpreted as the consequence of star formation feedback. At low mass concentration, the potential well is not deep enough to retain the gas after supernovae explosion, and star formation is quenched, which leads to a lower SF efficiency in LSB galaxies. Following Dekel & Silk (1986), the energy provided by supernovae can be estimated as $E_{SN} \sim \epsilon \nu \, dM^*/dt \, t_{rad}$, where $\epsilon = 10^{51}$ erg is the energy released by one supernova, the frequency of supernovae per unit mass is $\nu = 1$ for $100 M_{\odot}$ stars formed, and the characteristic time t_{rad} marks the end of the adiabatic phase. This amount of energy from supernovae is able to disperse the gas (of mass M_g), when it equals its kinetic energy $1/2 M_g V^2$, where V is the rotational velocity of the galaxy. There is a transition in galaxy rotational velocity (or potential well depth) where the gas begins to outflow, at the critical velocity $V_{SN} \sim 100$ km/s, which corresponds in order of magnitude to the transition found between LSB and HSB.

2.1. Quenching of star formation

As shown in Figure 2, the main parameter determining the star formation efficiency is the stellar surface density. Below the critical value of $3 \cdot 10^8 M_{\odot}/\text{kpc}^2$, the average star formation rate per unit mass does not depend on mass or surface density, nor concentration. The scatter in star formation rate increases with surface density. The SFR is then more bursty, and depends essentially on the external gas accretion. Above the threshold in surface density, the galaxy growth through star formation shuts down. The time-scale to consume the gas is inversely proportional to the stellar surface density.

2.2. Origin of the bimodality

There is therefore two interpretations for the origin of the bimodality: either the total mass is the determining factor, and the transition occurs at the critical halo mass of $3 \cdot 10^{11} M_{\odot}$: above this halo mass, the external gas is not accreted cold, but is heated in shocks and then has no time to cool (subject in addition to AGN feedback, Dekel & Birnboim 2006); or above the critical surface density of stars of $3 \cdot 10^8 M_{\odot}/\text{kpc}^2$, the gas is quickly transformed into stars, and the time spent in the "blue" star-forming sequence is short. In this view, galaxies pass from the red sequence to the blue sequence and back, but the blue phase is much shorter at high mass and concentration than at low mass (Kauffmann et al. 2006).

3. Gaseous filaments around Galaxies

The numerical techniques are progressively refined to take into account colder gas, and simulate the cold gas infall. While still most simulations consider the "cold gas" to be at 10^4K only, infalling multi-phase gas has been studied by T. Kauffmann et al. (2006), and the cooling/heating of dense clumps is

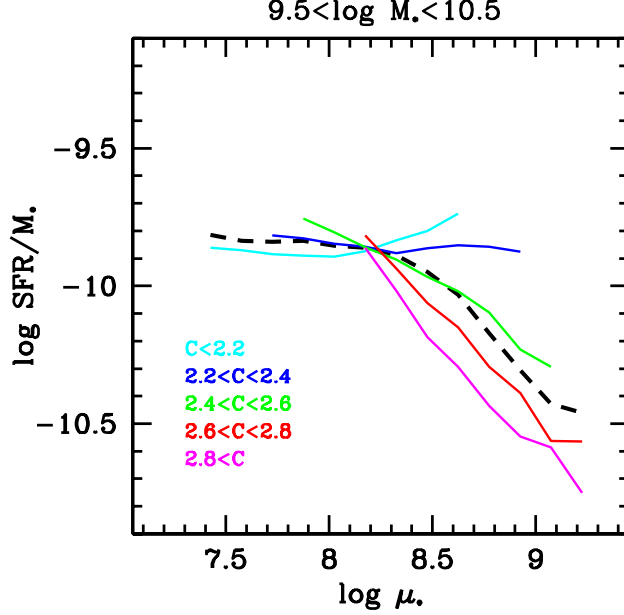


Figure 2. The star formation rate per unit stellar mass rate depends essentially on surface density, and on the concentration. Here this specific SFR is plotted versus surface density for masses between $3 \cdot 10^9$ and $3 \cdot 10^{10} M_{\odot}$, and different concentrations in different colours (the black dashed line is the total), from Kauffmann et al. (2006).

now introduced in the SPH scheme, through considerations of the H_2 and HD molecules (Maio et al. 2007).

The gaseous filaments are hard to observe, because of their low density and dilution. However, with the high sensitivity of present day deep searches, it is possible to see them at their connection to galaxies. The example of the edge-on galaxy NGC 891 is spectacular (Fraternali et al. 2007). Not only a thick gaseous envelope is seen at a thickness of 8kpc, but HI gas filaments are obvious up to 20kpc height above the galaxy plane. The rotational velocity of this gas decreases with z , and its origin cannot be due to a galactic fountain phenomenon, coming from the star formation feedback, which will conserve angular momentum.

In some galaxies, the fountain effect is detected in addition (for example the gas outflows in NGC 2403), while in general inflow is observed, like high velocity clouds (HVC, IVC) in the Milky Way. Gaseous haloes are only explained by accretion of external gas (Fraternali & Binney 2006).

4. Gas angular momentum lost in mergers

External gas infall could help to solve the problem of the angular momentum catastrophe, and the formation of too small galaxy disks in the conventional scenario (Navarro & Steinmetz, 2000). The gas loses its angular momentum essentially through mergers, but not during cold accretion (D’Onghia et al. 2006). Tidal torques and the corresponding dynamical friction during galaxy interactions transfer the gas orbital angular momentum to the more extended dark matter (e.g. Barnes & Hernquist 1992), but also to the extended gas in the outer filaments (see Figure 3). After a violent merger, the gas has condensed in a compact disk, of radius lower than 3.5 kpc. Only diffuse cold accretion after the last merger can reform an extended disk, but only a small fraction of the baryonic mass is then in the extended disk (larger than 3.5 kpc). This gas accretion can be done either by smooth gas, or substructures less than 1/10th in mass, which are easily stripped.

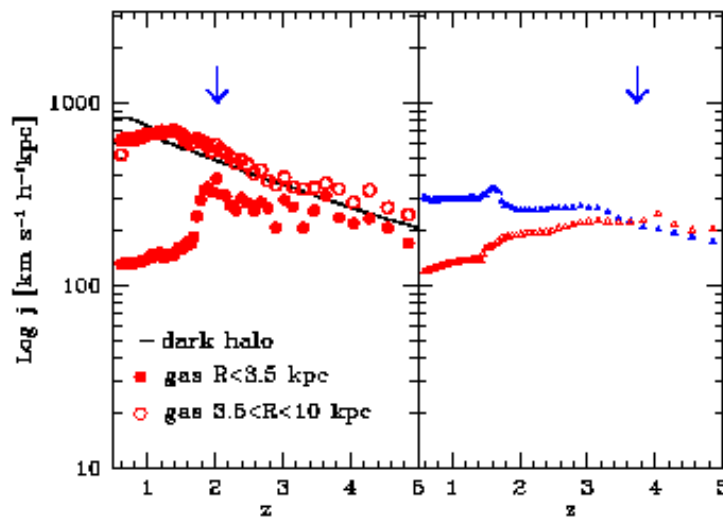


Figure 3. How galaxies lose their angular momentum, during Λ CDM simulations: the left panel shows the specific angular momentum as a function of redshift of the dark matter (solid line) and the gas in the compact central disk (filled circles) or the gas in the envelope (empty circles). The right panel shows the evolution of the angular momentum of the dark matter (blue curve) or the gas (red curve) of the massive progenitor that has already formed a compact disk at $z=2$, from D’Onghia et al. (2006).

Since each major merger exchanges angular momentum between the baryons and dark matter, the latter could be expected to possess more specific angular momentum, in haloes having experienced more mergers. In fact, this does not appear to be the case in numerical simulations, since after a certain period of relaxation, the excess of angular momentum is expelled from the halo through the virial radius (D’Onghia & Navarro 2007). The specific angular momentum

is a function of radius, and its excess yields the expansion of the particles, and inflation of the haloes.

Why the angular momentum problem is still not solved

To keep a significant angular momentum in baryonic disks, there should be cold gas accretion along cosmic filaments after the last major merger, where occurs the angular momentum loss. To form substantial disks, there should be no major mergers from $z=1$ until the present time, but this is not likely, in the hierarchical scenario, and according to cosmological simulations. Statistically, there exists dark haloes without any merger after $z=1$, and subsequent gas accretion will then explain extended gas disks around big bulges. But the main problem is to form spiral disks, without any bulge at $z=0$.

The gas inflow from filaments has an angular momentum direction generally offset from that of the galaxy disks. This skewed accretion will in general create warps, and progressively re-orient the spins of galaxies (e.g. Jiang & Binney 1999). When the offset is extreme, and the accretion is perpendicular, then polar rings could be formed (Maccio, Moore & Stadel 2006). This is an efficient way to form such systems, which reveal young disks around early-type systems. In polar ring galaxies formed in such accretions, the dark matter component is predicted to be quite round, at least in the region of the visible galaxy.

5. Infall of gas and galaxy dynamics

5.1. Star formation history in spirals

In order to reproduce the observed abundances of metals, models of the chemical evolution of the Milky Way require a continuous infall of gas with metallicity about 0.1 times the solar value. Infall is required in particular to solve the well-known G-dwarf problem, i.e. the observation of a very narrow range in metallicity for most long-lived stars near the Sun. The infall of gas is also supported by the constant or increasing star formation rate (SFR) scenario inferred from the local distribution of stars (e.g. Haywood, Robin & Creze 1997). Other abundance problems require also an infall rate integrated over the entire disk of the Milky Way of a few solar mass per year at least (Casuso & Beckman 2001). This infall dilutes the enrichment arising from the production of heavy elements in stars, and thereby prevents the metallicity of the interstellar medium from increasing steadily with time. Some of this gas could come from the High Velocity Clouds (HVC) infalling onto our galaxy disk (Wakker et al. 1999).

In M31, HST colour-magnitude diagrams reveal that there exists a similar G-dwarf problem, even more severe than in the Milky Way (Worthey & Espana 2004). Here also closed-box models cannot explain the stellar distributions. The star formation rate in spirals in the middle of the Hubble sequence has also kept of the same order of magnitude over the Hubble time, instead of the expected exponential decrease expected from closed box models (e.g. Kennicutt et al. 1994), and favors gas accretion.

5.2. Secular evolution

Gas accretion is an essential ingredient for secular evolution driven by bars and spirals. Without gas, stellar disks are heated by spiral waves, and become featureless, or only barred after several dynamical times. Gas accretion can maintain spiral structure, and also can reform bars, which are weakened or destroyed in the evolution. Bar/spiral gravity torques produce radial gas inflow, and nuclear starbursts. Dynamical instabilities then regulate themselves, since the gas inflow itself can destroy the bar. The bar destruction involves two mechanisms: first the central mass concentration built after the gas inflow, destroys the orbital structure sustaining the bar, scatter particles and push them on chaotic orbits. Second, the gas inflow itself weakens the bar, by exchanging its angular momentum to the stars forming the bar (Bournaud, Combes & Semelin 2005).

Secular evolution then includes several bar episodes in a galaxy life-time. A spiral galaxy rich in gas (at least 5% of the disk mass) is unstable with respect to bar formation. Gravity torques are then efficient to drive the matter inwards. The galaxy morphological type evolves towards early-types, the mass is concentrated, the bulge is developed, through horizontal and vertical resonances. This weakens the bar, and when the galaxy becomes again axi-symmetric, gas can be accreted from the outer parts by viscosity (Bournaud & Combes 2002). The gas accretion, if significant with respect to the disk mass, can reduce the bulge-to-disk ratio (by replenishing the disk), and make the galaxy disk unstable again to a new bar.

5.3. AGN fueling

Gas flows due to bar gravity torques are an attractive explanation to explain AGN fueling. However, low-luminosity AGN, such as Seyfert galaxies are not observed in good correlation with bar strength. This could be due to the widely different time-scales between the gas flows from the outer parts of galaxies to the nuclear region (100pc-1kpc) and the nuclear short time-scales. Also, the fact that gas flows destroy the bar could play a large role in this absence of correlation.

More details in the evolutionary scenario have been searched through the gas mapping at high resolution in a dozen of Seyfert galaxies by the NUGA project (e.g. Garcia-Burillo et al. 2005). In most galaxies, gas has been found concentrated in rings at inner Lindblad resonances (ILRs), and the nuclear torques were measured positive, meaning that no fueling was occurring.

The accumulation of the gas into ILR rings is the first step of the secular evolution scenario, in galaxies where mass is concentrated in bulges, which is likely for spiral galaxies with massive central black holes. Through bar torques, the gas is driven inwards from corotation to the ILR, and accumulates in the ring, usually the site of active star formation. Since the sign of the torques change at resonance, positive gravity torques then prevent the gas to flow further in: under the bar forcing, gas inside the ring is evacuated outwards. Only in the central 10pc around the black hole, the potential is mostly axi-symmetric, and viscosity could help to fuel the AGN. A more consequent feeding has to wait the weakening of the bar, through the gas flows. Then the gas of the nuclear ring is liberated to form a smoother disk through viscosity which has become competitive against gravity torques.

The AGN fueling in early-type spirals can be viewed as a two step process: first gravity torques bring the gas of the large-scale disk to the nuclear ring, and when the dynamical feedback has weakened the bar, the viscous torques smooth out the ring, and bring gas to the central 10 pc, where it is under the influence of the keplerian potential of the black hole. The disk becomes axi-symmetric and the cycle can be restarted at its first step. In particular, the disk will be prone to a new bar instability if gas is accreted from the outer parts of the disk. In any case, the AGN phase is always correlated with a weak bar phase.

Only in one galaxy, NGC 2782 (Hunt et al. 2007), the nuclear torques have been measured negative, and the fueling caught in action (see Fig 4). This means that the fueling phase is very short, and only a minor fraction of active galaxies are observed in this phase.

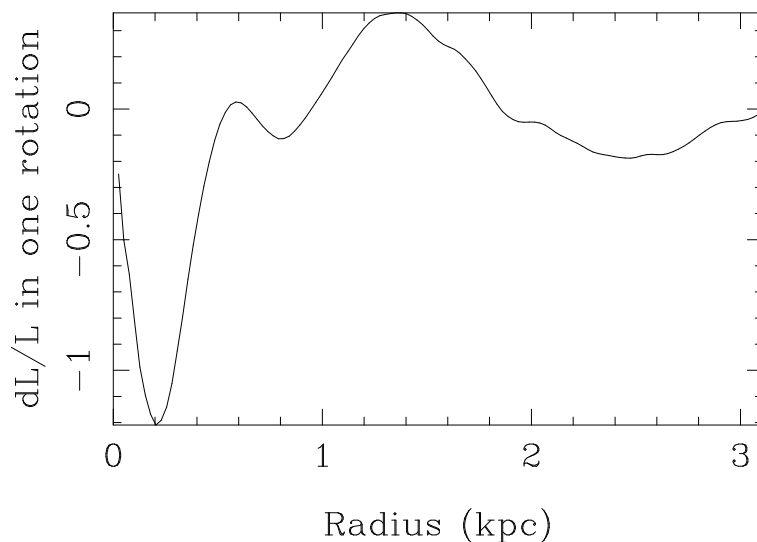


Figure 4. Estimation of the gravity torques, and the relative angular momentum lost by the gas in a rotation period (L is the angular momentum perpendicular to the disk). The torque is negative towards the center, which means the gas is fueling the AGN in NGC 2782 (Hunt et al. 2007).

6. Cooling flows in galaxy clusters

Galaxy clusters are interesting to study in the context of gas accretion, since they are certainly the prototype model of "hot accretion" in massive dark matter haloes. Since the hot gas is observed, and contains most of the baryons, it can be sure that cold accretion is restricted to a minimum. The cooling time of the gas at the center of clusters becomes smaller than the Hubble time, so an important gas flow has been predicted since many years. Now the cold gas has been observed (23 detected galaxies in CO at 2.6mm, Edge 2001; Salomé & Combes 2003), but the amplitude of the flow is 10 times lower than expected in the early times. Moreover, X-ray lines reveal gas down to a temperature of 2keV but not below (Peterson & Fabian 2006).

The last decade results from the Chandra & XMM satellites have established that the cooling flow phenomenon is self-regulated. The simple view of spherical unimpeded flow is now completely revised, to take into account the re-heating processes, the feedback due to the active nucleus or black hole: shocks, radio jets, acoustic waves, bubbles... The cooling gas is not only observed in the CO emission, but also directly from the pure rotational lines of the H_2 molecule. For instance, large molecular masses are infalling onto the central galaxy in Perseus (Johnstone et al. 2007). The H_2 lines have been surprisingly strong in many cooling flow clusters, as discovered by Spitzer (e.g. Egami et al. 2006).

6.1. Amount of cooling gas

One of the puzzle in cooling flows was that the gas between temperature 10^4 and 10^7K was not seen with the expected amount. Gas at $T = 10^{5.5}\text{K}$ is now seen in the OVI emission (with FUSE) in many clusters, for instance in A1795 and Perseus (Bregman et al. 2006), giving cooling rates of $\sim 30 \text{ M}_\odot/\text{yr}$, about 3 times lower than previously expected.

The cold gas masses detected through CO emission are compatible with these cooling rates. The masses derived are conservative, since obtained with the same CO-to- H_2 conversion factor as solar metallicity spiral galaxies. Masses are between $3 \cdot 10^8$ and $4 \cdot 10^{10} \text{ M}_\odot$ (Edge 2001; Salomé & Combes 2003). In some cases, high resolution maps have been performed with millimeter interferometers, and it was clearly established that the CO emission is not correlated with any central galaxy, but is originating from the cooling flow. The CO gas kinematics is related to the cluster and is not rotation around the central galaxy. This is the case for Abell 1795, where a cooling wake is observed in X-ray (Fabian et al. 2001). The cooling rate has been estimated to $200 \text{ M}_\odot/\text{yr}$ inside a radius of 200kpc (Ettori et al. 2002). The CO emission has been shown to follow the cooling wake (Salomé & Combes 2004), and also the 60kpc $\text{H}\alpha$ filament mapped by Cowie et al. (1983). The main CO velocity is centered on the cluster velocity. In Perseus, the CO emission follows the conspicuous $\text{H}\alpha$ filamentary structure, mapped by Conselice, Gallagher & Wyse (2001). Again the molecular component is not in rotation in NGC 1275 (Salomé et al. 2006). The radio jets from 3C84 create holes and bubbles in the hot gas, which is compressed at the boundaries, and cools faster. This means that cold clumps could be found far from the central cooling activity.

Two main models are therefore advanced to account for cooling and heating processes: hot and cold feedback. In the first point of view of hot feedback, the hot ICM cools and is accreted close to the AGN. Then the observed cold gas far from the center should come from galaxies. In the cold feedback scenario, cold gas is accreted on large scales. Cooling can occur at large distance because of non-linear over-dense blobs, created in wide regions due to past AGN activity, which decrease the cooling time-scale for these perturbed regions (e.g. Pizzolato & Soker 2005). In this point of view, there is co-existence of multi-phase (cold and hot) gas.

6.2. Numerical simulations

The cold feedback scenario has been considered in recent multi-phase simulations of the cluster environment (Revaz, Combes & Salomé 2007). The AGN feed-

back is schematized by following hot bubbles, during their buoyant rise across the cluster. Very cold gas is spontaneously formed by the perturbation of the hot ICM, and forms a filamentary structure in the wake and in the rim of the bubbles. The amount of cold gas formed and its kinematics are in agreement with observations of CO and H α .

The AGN feedback is therefore not only negative in re-heating the cooling gas, but also positive in allowing some further gas to cool.

Alternatively, the hot feedback scenario has been also simulated by Cattaneo & Teyssier (2007). They show that the catastrophic cooling is regulated by the AGN jets, and a stationary state can be reached, to reproduce observations (see Fig 5). The cooling gas is regulated to just the right amount required to fuel the AGN activity.

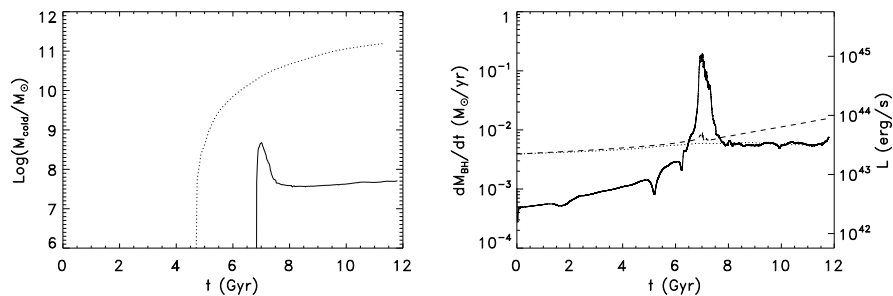


Figure 5. AGN feedback in cooling flows. The left panel shows the mass of the cold gas as a function of time, in the cooling flow simulation (dotted line), and with AGN feedback (solid line); the solid line in the right panel shows the accretion rate by the black hole (left axis) or the corresponding jet mechanical luminosity (right axis) in the simulation with AGN feedback. The dashed line shows the X-ray emitted by the ICM in the same simulation, compared with the dotted line without feedback, from Cattaneo & Teyssier (2007).

7. Conclusions

Cold gas accretion along cosmic filaments is an important way to form and grow galactic disks. In particular cold gas accretion dominates at high redshift. Simulations with enough resolution reveal that all the gas is not shock heated at the virial radius, as in the usually adopted paradigm.

The cold accretion is a way to solve the angular momentum problem in the formation of galaxy disks. In the hierarchical scenario, the angular momentum of baryons is lost in mergers to the dark matter haloes. The gas accreted after the last merger does not lose angular momentum, and is able to form large disks, although around already massive bulges. The baryons will keep more specific angular momentum globally, if galaxy formation does rely more on smooth matter accretion than mergers.

Gas accretion is also required for disk evolution, being one of the main actor of secular evolution. It is needed to maintain spiral structure, reform bars, asymmetries, warps..

Cooling flows in galaxy clusters are a prototype example of hot accretion. Cold gas observed in CO and H₂ line emission is now compatible with the expected revised cooling rates. The cooling process is self-regulated through AGN feedback. The hot feedback scenario considers that the self-regulation can occur close to the central AGN, while cold feedback involves a much wider region, where dense clumps of gas can cool far from the AGN. This scenario could explain the large-scale filamentary structure observed in CO and H α in nearby cooling flows.

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